HYDRAULIC CONDUCTIVITY OF A DENSE PREHYDRATED GCL: IMPACT OF FREE SWELL AND SWELLING PRESSURE

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Abstract: Exposure to liquids with high electrolyte concentrations or high cation valence present in landfill leachates can cause significant increases in hydraulic conductivity of clays due to a reduction in the thickness of the double layer. Methods to prevent compression of the interlayer are: prehydration of the bentonite, compression with increasing the solids content and addition of polymers. The aim of this study is to evaluate the performance of a Dense PreHydrated GCL (DPH GCL) compressed during manufacturing and pre-hydrated with a polymeric solution. A series of hydraulic conductivity tests with deionised water, sea water and a 0.01 M CaCl2 solution were performed on single sheet and overlapped DPH GCL samples. Free swell and swelling pressure tests have also been performed with this solutions and with a series of KCl and $CaCl_2$ solutions with a concentration varying from 0.001 M to 1 M. The overlapped samples were analysed in large scale laboratory permeameters at different effective stresses. In addition, swelling pressure tests on single sheet samples were conducted to analyse the swelling behaviour of the factory prehydrated GCL. The concomitant effect of prehydration, addition of polymeric compounds and densification increased the hydraulic performance of GCLs under aggressive conditions. The use of bentonite paste to seal the overlap in presence of seawater was shown to be crucial. The swelling pressure test may be proposed as an alternative to the swell index test to characterize the swelling behaviour of polymer prehydrated GCLs.

Keywords: Geosynthetic Clay Liner, Bentonite, Hydraulic Permeability, Dense Polymeric Prehydration, Overlap, Swell Pressure.

INTRODUCTION

Geosynthetic Clay Liners (GCLs) have gained widespread popularity as a substitute for compacted clay liners (Schakelford et al. 2000, Bouazza 2001, Katsumi and Fugakawa 2005). A significant increase of hydraulic conductivity of sodium bentonite in GCLs can occur for high concentrations, high valence of the ions and to low dielectric constants of the permeant solutions due to a reduction in the thickness of the Diffuse Double Layer (DDL) (Mitchell 1993, Ruhl and Daniel 1997, Shackelford et al. 2000, Egloffstein 2001, Katsumi and Fugakawa 2005). Prehydration of the bentonite, increase of the solids content and the addition of polymers can prevent or minimise the compression of the DDL. A number of chemically-resistant bentonites treated with polymers have been recently developed to improve the chemical compatibility to potentially aggressive permeants (Kondo 1996, Onikata et al. 1996, Lo et al. 1997, Mazzieri et al. 2005, McRoy and Ashmawy 2005).

In this study a Dense PreHydrated GCL (DPH GCL) is evaluated. The prehydration of this GCL is obtained during manufacturing with addition of polymeric compounds. The DPH GCL is compressed by calendaring under vacuum during manufacturing to a dry bentonite mass per unit area of 5.43 kg/m2 (much higher than the 3.7-4.0 kg/m2 of conventional GCLs).

A few studies in the literature (Schroeder et al. 2001, Kolstad et al. 2004, Katsumi et al. 2008) are available concerning the compatibility test of Dense PreHydrated (DPH) GCLs. They showed that the nature of the tested permeating fluids had no major influence on the hydraulic performance of single sheet samples. The authors are not aware of published experimental data concerning the hydraulic conductivity of overlapped DPH GCL samples permeated with high electrolyte solutions such as the sea water and the $CaCl_2$ solutions used in this research.

The hydraulic conductivity of seams is crucial to the overall performance of GCLs as hydraulic barrier. Large-scale apparatuses able to accommodate a full-scale overlap seam are necessary to test correctly the efficiency of the seams. In this study large scale laboratory tests were conducted on DPH GCL samples with the overlap width expected on site. The impact of the swelling pressure on the overlap sealing performance was evaluated.

MATERIALS

Dense Prehydrated (DPH) GCL

A manufactured DPH GCL has been analysed. This patented GCL (Flynn and Carter 1998) is prehydrated with a dilute polymeric solution containing sodium carboxymethyl cellulose (CMC), sodium polyacrylate (PAAS) and methanol. The sodium-montmorillonite clay is mixed with the liquid in a high speed, high shear mixer, this mass is then calendared under vacuum into a bentonite sheet with a reduced number of voids.

The high shear mixing, the under vacuum calendaring, the use of methanol as a solvent and the evaporation at high temperatures enhance the adsorption of polymers in clays encouraging the formation of a complex by intercalation (Onikata et al. 1999, Filippi et al. 2007, Sinha Ray and Bousmina 2005, McRoy and Ashmawy 2005). Such adsorption is often irreversible because it is energetically favoured (Theng 1982, Daniels and Inyang 2004).

A bentonite paste provided by the manufacturer of the DPH GCL was used to improve the sealing of the overlapped samples. The bentonite paste is likely prehydrated with the same polymeric solution used for the DPH GCL. The water content of the bentonite paste is higher than the water content of the DPH GCL sample (144.30% vs. 44.82 %) in order to enable an easy spreading of the paste.

Table 1 summarises the main properties of the DPH GCL analysed.

Table 1. Physical and chemical properties of the DPH GCL

Property	Value	Source
dry mass of bentonite (ASTM D5993)	5.43 kg/m^2	
average core thickness	4.9 mm	
water absorption	550 %	specification sheet
spec. gravity of solids (ASTM D854)	2.56	
w% (ASTM D2216)	44.82%	
Montmorillonite content	90%	specification sheet
pH (1:5 extract)	8.21	
EC (1:5 extract)	3580 µS/cm	
CEC	51.8 meq/100g	
exchangeable cations		
Na (1+)	77.71 meq/100g	
K (1+)	2.39 meq/100g	
Ca (2+)	12.43 meq/100g	
Mg (2+)	8.57 meq/100g	
soluble salts		
Na (1+)	4.39 meq/100g	
K (1+)	0.11 meq/100g	
Ca (2+)	0.37 meq/100g	
Mg (2+)	1.43 meq/100g	
Cl (1-)	2.75 meq/100g	
S04 (2-)	6.14 meq/100g	
HCO3 (1-)	0.30 meq/100g	
PO4 (3-)	0.05 meq/100g	

Permeant solutions

The permeant solutions used for the hydraulic conductivity tests are: 1) deionised water (DW); 2) natural sea water (SW); 3) 0.01 M $CaCl_2$ solution. These solutions were chosen to investigate the impact of aggressive electrolyte solutions on the hydraulic conductivity performance of overlapped DPH GCL samples.

Free swell and swelling pressure tests have also been performed with DW, SW and a series of KCl and CaCl2 solutions with concentrations varying from 0.001 M to 1 M. This solutions were used to study the impact of concentration and valence on the swelling performance of the polymer treated bentonite.

The testing solutions were prepared by dissolving powdered salts in DW. The sea water was collected in the Adriatic Sea near Portonovo (Ancona, Italy). Chemical composition of the sea water is shown in Table 2.

When gas bubbles arose from the inlet and effluent lines during the hydraulic conductivity tests, presumably due to microbial activity, the influent solution was spiked with a DOWICIL QK-20 ® biocide solution (500 ppm). When the hydraulic conductivity showed high values the influent solution was spiked with a Rhodamine dye (5 g/L) to stain the possible preferential flow paths.

Table 2. Chemical composition of the sea water

Ions	Concentration (M)
Na (1+)	0.501
K (1+)	0.012
Ca (2+)	0.011
Mg (2+)	0.049
Cl (1-)	0.547
SO4 (2-)	0.027
HCO3 (1-)	0.003
CO3 (2-)	0.0003
NO3 (1-)	0.0007
Electrical Conductivity	55 mS/cm
salinity	35.5
pH	7.89

METHODS

Free swell tests were conducted following the ASTM D5890. Bentonite paste and bentonite from the DPH GCL were dried in the oven at 105°C. After drying, the bentonites were ground using a mortar and pestle until 100% passed the 200 mesh U.S. standard sieve. 90 ml of the testing solutions were poured into a 100 ml graduated cylinder. Two grams of sieved bentonite were placed in the aqueous solutions in the cylinder in 0.1 g increments. After the 2 g were added, additional solution was poured to fill the cylinder to the 100 ml and to rinse any particle of bentonite adhered to the internal sides of the cylinder. After 16 hours of hydration period after the last increment, the final temperature and the volume of swollen bentonite were measured.

The swelling pressure test apparatus used in this study consists of a stainless steel ring (5 cm diameter) accommodated in a standard one-dimensional oedometer cell, located in a frame provided with a load cell connected to a computer. The sample was obtained from a DPH GCL sheet using a stainless steel cutting ring. The ring was then placed into the oedometer cell that was inundated with the testing solution. The swelling pressure was measured by the load cell keeping the height of the sample constant. The achievement of a steady maximum swelling pressure was chosen as termination criteria.

Falling-head hydraulic conductivity tests were conducted in flexible and rigid wall permeameters following the ASTM D5084 and D5856. A standard permeameter for 10 cm diameter samples was used for the reference hydraulic conductivity values on single sheet samples. A large-scale laboratory permeameter that can house two specimens was used to test 30 cm diameter samples with 10 cm overlap permeated with deionised and sea water. A rigid wall permeameter was used to test 14 cm diameter samples with 5 cm overlap seams permeated with a CaCl2 0.01 M solution.

The hydraulic conductivity tests in the flexible wall permeameter were performed with an average effective stress of 14 kPa and a back pressure of 340 kPa. In order to analyse the impact of increasing the effective stress on the hydraulic performance of the overlap, effective stresses of 14 kPa, 28 kPa, 55 kPa and 110 kPa were applied. The hydraulic conductivity tests in the rigid wall permeameter were performed with an average effective stress of 14 kPa and a back pressure of 14 kPa.

The results of the hydraulic conductivity tests have been expressed in terms of permittivity because for GCLs that are thin compressible and highly swellable specimens the thickness does not need to be measured. The permittivity of a soil specimen is indeed the ratio between the hydraulic conductivity and the average specimen thickness.

RESULTS AND DISCUSSIONS

Hydraulic Conductivity

Table 3 shows an overview of the tests performed and the results in terms of hydraulic permittivity, swell index and swell pressure of the DPH GCL single sheet and overlapped samples permeated with deionised water, sea water and a 0.01 M $CaCl_2$ solution. The single sheet samples analysed maintained a low permittivity in deionised water, sea water and in $CaCl_2$, as shown in Figure 1.

Table 3. Hydraulic conductivity test overview.

Test	diam.	overlap width	permeant	effective stress	swell index	swell pressure	hydraulic permittivity
	[cm]	[cm]		[kPa]	[ml/2g]	[kPa]	[s^{-1}]
single sheet	10	-	DW	14	16.0	298.13	7.61E-10
			DW (biocide)	14	18.0	298.13	7.72E-10
			SW	14	8.3	34.36	2.74E-10
			$CaCl_2$ 0.0125 M	14	-	-	9.55E-10*
overlap	14	5	$CaCl_2$ 0.01 M	14	28.0	160.39	4.07E-09
overlap	30	10	DW	14	16.0	298.13	8.85E-10
				28	16.0	298.13	4.92E-10
				55	16.0	298.13	1.95E-10
				110	16.0	298.13	1.67E-10
	30	10	SW	14	8.3	34.36	3.68E-06
				28	8.3	34.36	1.45E-06
				55	8.3	34.36	1.06E-06
				110	8.3	34.36	2.51E-07
with paste	30	10	DW (biocide)	14	18.0	298.13	1.44E-09
	30	10	SW	14	8.3	34.36	1.46E-09
bentonite paste	-	-	DW	-	13.5	-	-
			SW	-	7.9	-	-

* Mazzieri et al. 2008

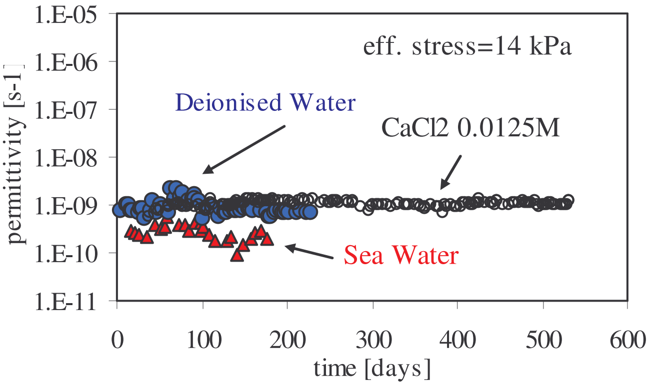


Figure 1. Hydraulic Permittivity of single sheet DPH GCL samples permeated with deionised water, sea water and a $CaCl_2$ 0.0125 M solution

At low applied stresses the high swellable GCLs increase their height and their bulk void ratio with a consequent high permeability. Mesri and Olson (1971) demonstrated that for a given permeant such as deionised water, there is a linear relationship between the bulk void ratio and the hydraulic conductivity (both in log scale).

The hydraulic conductivity of the DPH GCL to deionised water was lower than for a conventional GCL (tested by Petrov et al. 1997, the conventional GCL had the same montmorillonite and dry bentonite content of the DPH GCL) even under a lower effective stress. The hydraulic conductivity of the DPH GCL was in fact 6.81E-10 cm/s in deionised water under 14 kPa vs. 1.20E-09 cm/s of the dry GCL to deionised water under 35 kPa. Swell of the DPH GCL in deionised water and in $CaCl_2$ caused a higher bulk void ratio than in sea water which resulted in a slightly larger hydraulic conductivity (6.81E-10 cm/s in deionised water, 7.80E-10 cm/s in $CaCl_2$ and 1.45E-10 cm/s in sea water which correspond respectively to a final height of 0.89cm in DW, 0.77cm in $CaCl_2$ and 0.60 cm in SW).

The overlapped samples showed a permittivity comparable to the single sheet for the sample permeated with DW, slightly higher on the sample permeated with $CaCl_2$ and four orders of magnitude higher on the sample permeated with SW (Figure 2).

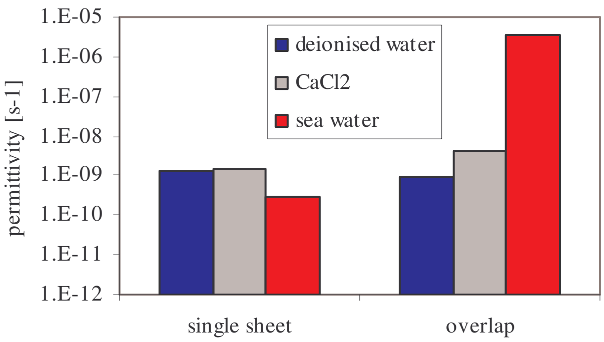


Figure 2. Hydraulic Permittivity of overlapped DPH GCLs permeated with deionised water, sea water and a $CaCl_2$ 0.01 M solution compared with the permittivity of the single sheet samples (effective stress 14 kPa)

At this point the impact of the increase of the effective stress on the hydraulic permittivity of the overlap to sea water was analysed. As expected a decrease of the permittivity has been noticed increasing the effective stress in four steps from 14 kPa up to 110 kPa (Figure 3a), but the improvement was not satisfactory to achieve the desired hydraulic performance to sea water.

The swelling of the DPH GCL in sea water was very low. We suspected that the reason of the high permittivity of the overlap to sea water is that the bentonite did not swell sufficiently to pass trough the geotextile mesh and to seal to the upper GCL sheet. To demonstrate this hypothesis, at the end of the test, a coloured dye was added to the influent solution to stain the flow paths of the sample permeated with SW. Inspection of the GCL during disassembly showed that dye was homogeneously spread in the inlet filter paper, while at the outlet it was present mainly in the overlapped area, indicating that flow was primarily passing through the overlap causing an increase in permittivity. For this reason bentonite paste was added to the overlap with a considerable improvement as shown in Figure 3b. The permittivity of the overlap with bentonite paste to sea water (1.46E-09 s^{-1}) was comparable to the permittivity to deionised water (1.44E-09 s^{-1}).

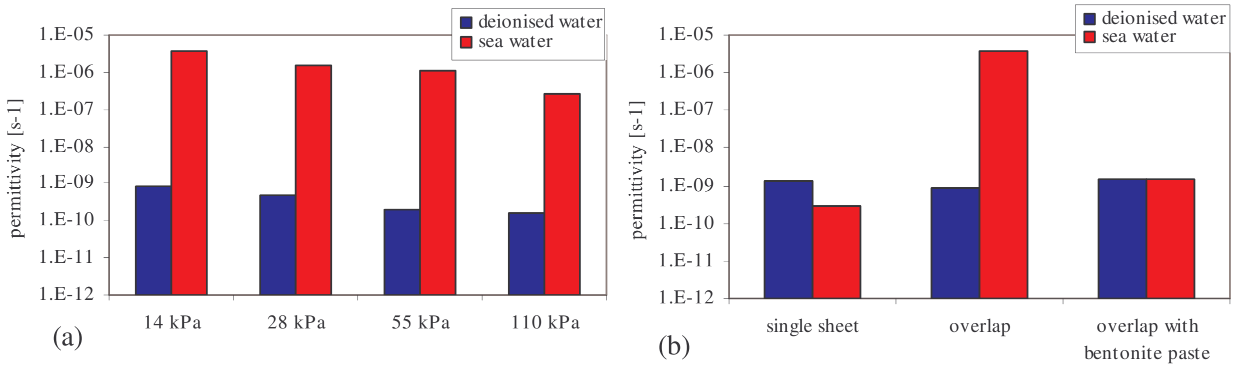


Figure 3. Decrease of the Hydraulic Permittivity of overlapped DPH GCLs to deionised water and sea water: (a) by increasing the effective stress from 14 kPa to 110 kPa and (b) by adding a polymeric moistened bentonite paste

Free swell and swelling pressure

Figure 4 shows that for concentrations higher than 0.01 M the swell volume of the bentonite contained in the DPH GCL decreased with increasing ion concentration and valence which is consistent with previous findings on untreated bentonites (Jo et al. 2001). On the other hand, the figure shows that for low concentrations the trend seems to be opposite because of the dispersant properties of the polymers contained in the DPH GCL bentonite. The observed surnatant of these solutions were in fact turbid, increasing turbidity with decreasing concentration and valence. Turbidity of the surnatant implies that part of the bentonite remain in suspension and does not contribute to the final swelling volume, producing a false measurement.

Swelling pressure tests were performed to overcome this situation and to represent the actual swell performance of the polymeric prehydrated samples. Figure 5 shows that the swelling pressure results were not affected by the dispersant properties of the polymers. The swell pressure decreases in fact monotonically with increasing concentration and valence. Figure 6 plots the relationship between the swell pressure of the DPH GCL and the ionic strength of the chemical solutions. The swell pressure of the DPH GCL decreases exponentially with increasing the ionic strength of the chemical solutions used, which is consistent with the Double Layer Theory.

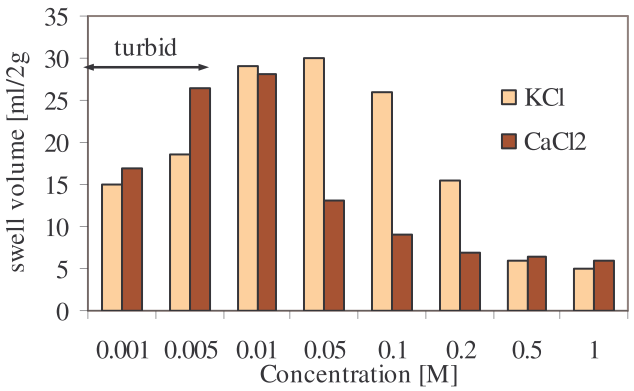


Figure 4. Swell volume of the polymer treated bentonite obtained from the DPH GCLs to KCl and $CaCl_2$ solutions increasing the concentration and valence: effect of the dispersant properties of the polymers at low concentrations

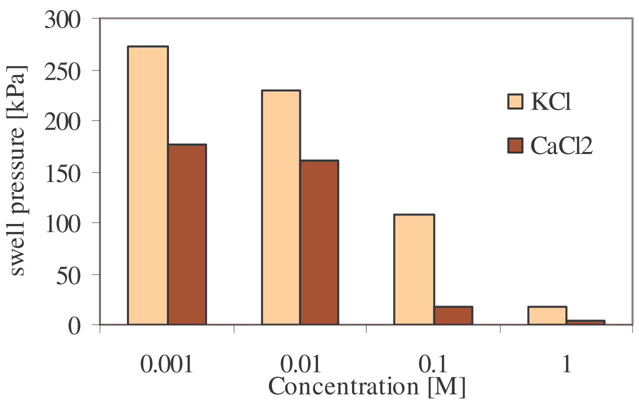


Figure 5. Swell pressure of the DPH GCL in KCl and $CaCl_2$ solutions with concentrations varying from 0.001 M to 1 M: the swell pressure decreases monotonically with increasing concentration and valence

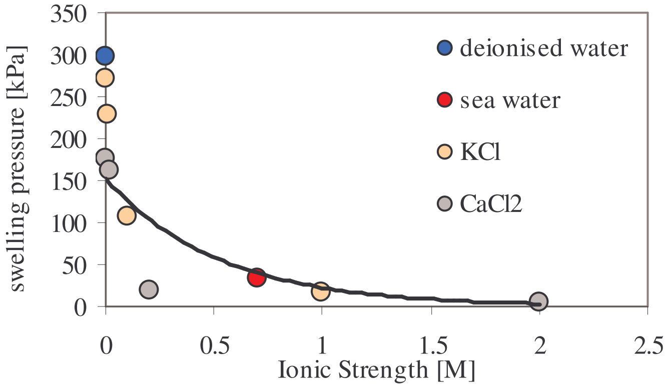
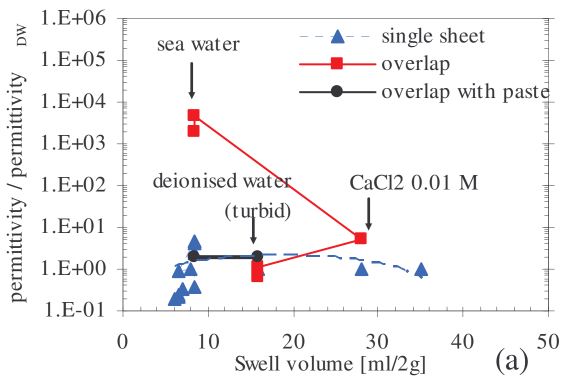


Figure 6. The swell pressure of the DPH GCL analysed vs. the ionic strength of the chemical solutions used: the swell pressure decreases exponentially with increasing the ionic strength

There is a strong inverse relationship between hydraulic conductivity and swell volume for conventional dry GCLs (Jo et al. 2001). Conversely the hydraulic conductivity of the DPH GCL single sheet samples remained low independently of their swell volume, as shown by the blue triangles in Figure 7a. On the other hand, the overlap sealing does depend on the swell index, as shown by the red squares in Figure 7a. Although, with the use of bentonite paste the permittivity of the overlap was low independently of the swell mechanism, as shown by the black circles in Figure 7a.

Figure 7b shows that the normalised permittivity decreases monotonically with increasing the swell pressure of DPH GCL overlapped samples (as shown by the red squares). Test results demonstrate that the swell pressure test may represent an alternative to the free swell test for indicating DPH GCL overlap sealing performance since the dispersant properties of the polymers did not affect the expected trend of the normalised permittivity vs. the swell pressure as it occurred for the swell index test (Figures 7a and 7b).



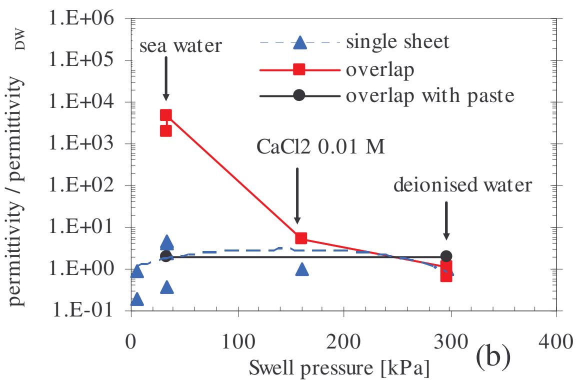


Figure 7. Hydraulic Permittivity normalised to the Permittivity to deionised water of single sheet and overlapped DPH GCLs samples: (a) plotted vs. swell volume and (b) vs. swell pressure

SUMMARY AND CONCLUSIONS

The concomitant effect of prehydration, addition of polymeric compounds and densification increased the hydraulic performance of DPH GCLs under unfavourable conditions, such as low effective stresses and high electrolyte concentrations.

Although the permittivity of single sheet DPH GCL samples remained low independently on the swell performance, the swell mechanisms is of fundamental importance to guarantee the sealing of the overlap in high electrolyte concentrations.

An increase of effective stress decreased the hydraulic conductivity of overlapped samples but not significantly to reach the target performance in SW. The use of bentonite paste showed to be crucial to maintain low permittivity to sea water of the overlapped DPH GCL.

The permittivity normalised to the permittivity to deionised water decreases monotonically with increasing the swell pressure of DPH GCL overlapped samples without bentonite paste. Test results demonstrate that the swelling pressure test may be proposed as an alternative to the swell index test for representing the sealing performance of the overlap of Dense Prehydrated GCLs treated with dispersant polymers.

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